Marine Physical Laboratory

Underwater Imaging Studies

Jules S. Jaffe

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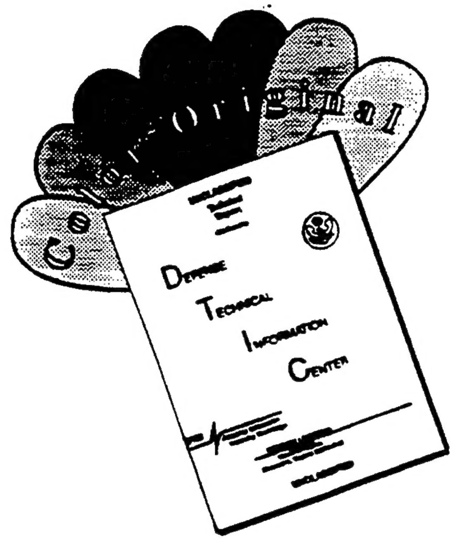

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Abstract

This project was concerned with advancing the understanding of both the theoretical underpinnings of underwater image formation theory and also the experimental development of a new system for obtaining 3-dimensional information about ocean optical properties. Theoretical results from a Monte Carlo simulation of underwater radiance fields the average cosine of the radiance field $\bar{\mu}$ does not achieve it's asymptote for an omnidirectional source, even after 15 attenuation lengths. In addition, limits to the computation of the absorption coefficient, using an omnidirectional light source are explored. Experimental results of lab simulations of a volumetric imaging system based on fluorescence emission from a sheet of stimulating light laser light indicated that the system can be used to measure the 3-dimensional distribution of chlorophyll-a over a broad range of concentrations.

Research Objective

The research objectives can be divided into two categories: 1) Increased use and enhanced scope of the Monte Carlo underwater computer model and; 2) Continued studies (experimental and theoretical) dedicated to

improving the range of applications and use of the 3-dimensional serial sectioning imaging system.

Research Summary

During the FY-94 funding period we have been working in a broad sense in the area of underwater imaging. This includes the development and examination of the results of Monte Carlo models and the continued exploration of the practical and theoretical aspects of underwater 3-dimensional imaging techniques. We consider both of these areas separately in the following discussion.

Underwater Imaging Simulation Using Monte Carlo Modeling

Work in this are has been concentrated on a joint paper with Robert Maffione of SRI/OSU where we have explored the dependence of the average cosine of the radiant field of an omnidirectional light source as a function of distance, water type, and the volume scattering function. The major results of the study are a comparison of experimental results recorded by Maffione et al. in the Lake Pend Oreille experiments with the output of the Monte Carlo model of Jaffe. In additional, theoretical results, mainly contributed by Maffione examine several interesting issues in looking at the radiance pattern from an isotropic light source.

Two volume scattering functions are used in the model, taken from Petzold to compute the radiance distributions at various distances from the source. The simulated radiance distributions are compared with measurements made at Lake Pend Oreille, Idaho, during the 1992 optical closure experiment. An analytic model is presented for $\bar{\mu}$ (the average cosine) which is valid to at least 15 optical lengths from the source. The model shows that the mean light path, derived form $\bar{\mu}$, is a strong function of the single scattering albedo and the Volume Scattering Function.

In addition, we found that errors in estimating the absorption coefficient by neglecting the increase in the mean light path, which is due to scattering, vary between 5% and 12% for nearly all natural waters. A mathematical proof is given that $\bar{\mu}$ goes to one as the distance to the isotropic point source goes to zero. An analytic expression is derived for $\bar{\mu}$ close to a finite diffuse-isotropic source which reveals that $\bar{\mu}$ approaches one as the distance decreases but at extremely close

distances, $\bar{\mu}$ goes to 1/2 as the distance to the surface of the source goes to zero. At distances beyond one optical length, $\bar{\mu}$ behaves essentially as it would for a point source. An asymptotic model for $\bar{\mu}$ as a function of the single scattering albedo is given with coefficients that depend on the VSF.

One of the most intriguing aspects of this paper is the observation of the asymptotic behavior of the light field at large numbers of attenuation lengths. As we have noted, in comparing the results of the paper to some asymptotic calculations that were done by C. Mobley (personal communication, 1994), the Monte Carlo results, even at 15 attenuation lengths do not seem to be very close to this asymptotic limit. Although this is somewhat surprising at first glance, especially when comparing this result to those measured when observing irradiance, the conclusion is less controversial when it is realized that in this paper we have computed radiance and that also, it is from a point source.

Three-dimensional Optical Serial Sectioning Technique

During the last year, we have continued to work on 3-dimensional techniques for computing underwater optical properties. Although our work has primarily been directed towards the computation of underwater chlorophyll-a using fluorescence, other applications are possible. We had our first major journal paper (in this area) published in Applied Optics this past May (Palowitch and Jaffe, 1994) and we have also had a paper accepted to the special JGR issue on Ocean Optics (S. Ackleson, editor). The latest paper focuses on the experimental aspects of the method and our demonstrated capability to invert for 3-dimensional chlorophyll-a in a series of laboratory experiments.

The demonstrated ability to acquire and discriminate between concentration levels of Chl-a show that an optical serial sectioning system can be used for volumetric fluorescence imaging. System capabilities have been determined with theoretical and experimental studies. Testing has shown that a resolution of .1 mg Chl-a /m^3 is achievable over a range from .1 to 23.0 mg Chl-a/m^3. Volumetric reconstruction of images with random noise added to the measured data demonstrated that the solution was not sensitive to error propagation. Sensitivity analysis conducted with 100 x 100 pixel planes and random noise input for each pixel confirmed the robustness of the reconstruction algorithm.

The lab demonstration of the system allowed a definition of system performance in terms of optical depth. Here, an optical depth of 0.97 (relative to the emission wavelength of 685 nm) indicates that the technique will allow imaging resolution over a 1 meter cube with 1 cm cubed spatial resolution. This lab demonstration of the performance of the system is configuration specific and can be improved. For example, with an improvement in light transmission (due to higher transparency of the filter), larger aperture (which will allow more photons to be collected) or more intense illumination, the optical depth of the system will be increased.

The three dimensional mapping capability indicates that the underwater sectioning system can be used as an in-situ Chl-a microscale mapping tool because of a demonstrated relationship between actual Chl-a levels and the computed values using the inversion algorithm. The calibration procedure provides a basis for adapting the prototype system to in-situ deployment.

The technique also has broad ramifications not only for ocean optics but also for oceanic biology. For example, other possible biological and physical oceanographic applications also exist. Predator prey interactions could be studied and models verified. Localized phenomena such as red tides could be mapped over time. With some implementation modifications and using Chl-a as a natural tracer, under ice fresh water/ salt water boundaries can be evaluated. A similar approach can also be used to analyze the effects of random fluctuations of turbulently generated shear on phytoplankton dispersion. Wind induced surface currents may also be tracked. In addition to studying biological and physical processes, possibilities exist for gaining insight into spatially varying inherent optical water properties with future multispectral scattering and absorption system modifications. Figure 1 shows a 3-dimensional Chl-a inversion from one of our series of laboratory experiments.

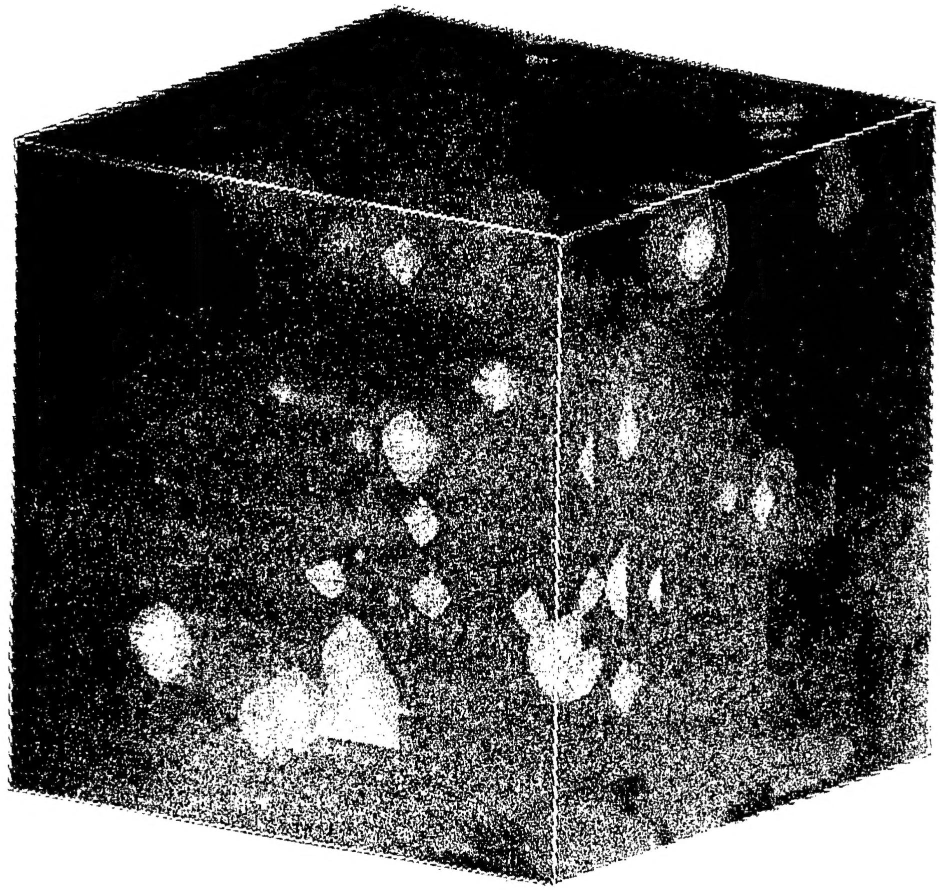

Figure 1. Three-dimensional reconstruction. Oblique view of three dimensional reconstruction of 12 cm x 12 cm phytoplankton distribution illustrated in Figure 5-15. Psuedocolor representation indicates concentration differences; black-low, blue-medium, green-high.

ONR Publications

Jaffe, J. S. "Monte Carlo modeling of underwater image formation: validity of linear and small angle approximations," Applied Optics.

Jaffe, J. S., E. Reuss, A. W. Palowitch, D. McGehee and G. Chandran, " New 3-D Acousto-Optic Instruments for Small Scale Oceanic Measurements, U. S. GLOBEC Newsletter, No. 6, April 1994

Palowitch, A.W.; Jaffe, J.S.," Three-dimensional ocean chlorophyll distributions from underwater serial-sectioned fluorescence images".Applied Optics, 10 May 1994, vol.33, (no.14):3023-33.

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